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# The Surprising Lunar Maria

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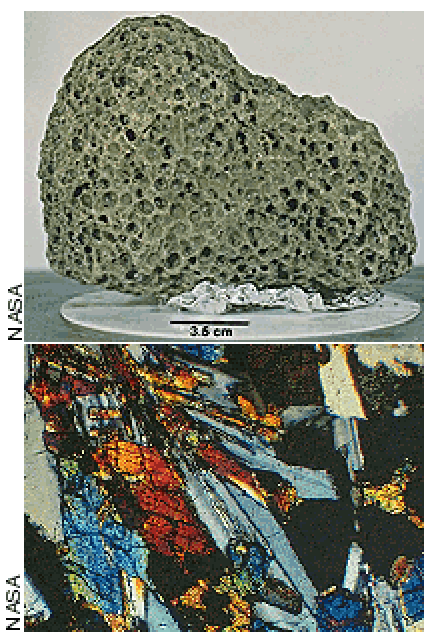
The lunar maria, the dark, smooth areas on the Moon, formed when lava flowed across the surface billions of years ago. Samples returned from the Moon by astronauts and by automated spacecraft suggested that the maria consist mostly of basalts with either low (less than about 5 wt%) or high (more than about 9 wt%) contents of titanium dioxide ($TiO_2$). Scientists wondered why there were so few lava flows with intermediate titanium concentrations, and they invented some elaborate, interesting explanations. However, the samples came from only a few places on the Moon. Recently, Tom Giguere and his colleagues at the University of Hawai'i used data from the Galileo and Clementine missions to evaluate the compositions of the maria over the entire lunar globe. Their results show that there are plenty of lava flows with intermediate amounts of $TiO_2$; in fact, there is a continuous spectrum of titanium contents from low (most abundant) to high (least abundant). This gives a different view of the nature of the lunar interior, and is consistent with the idea that the Moon melted soon after it formed.

**References**:

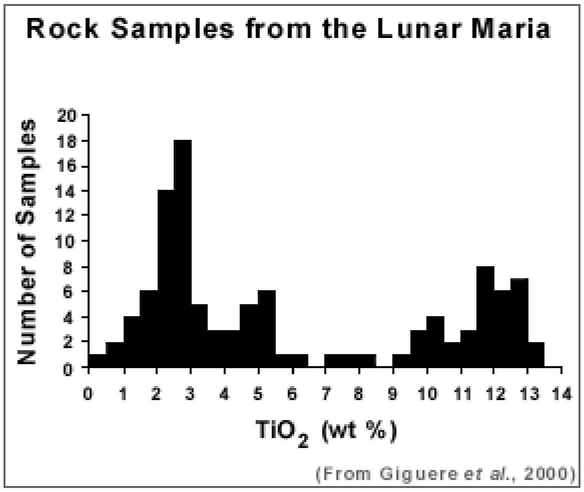
Giguere, T., Taylor, G. J., Hawke, B. R., and Lucey, P. G. (2000) The titanium contents of lunar mare basalts. *Meteoritics and Planetary Science,* vol. 35, p. 193-200.

## Moon Rocks




The samples returned by the piloted American Apollo missions and the robotic Russian Luna missions have been a rich source of precise data about the Moon. Chemical analyses of rocks from the lunar maria revealed a startling range in the amount of $TiO_2$ (titanium dioxide) present. (Chemists express analyses of rocks as oxides because most elements are chemically bound to oxygen in rocks.) However, with only a few exceptions, the rocks are either low in Ti (about 5 wt% $TiO_2$ or less) or high in Ti (more than 9 wt% $TiO_2$).

**Top:** Piece of mare basalt collected by astronauts during the Apollo 15 mission. The holes are bubbles of escaping gas trapped when the rock solidified. Such features, called vesicles, are common in lava flows on the Earth.
**Bottom:** Photograph taken with a microscope using polarized light of a thin slice (30 micrometers thick) of a mare basalt from the Apollo 15 mission. Yellow and orange mineral is pyroxene; grayish mineral is plagioclase feldspar.



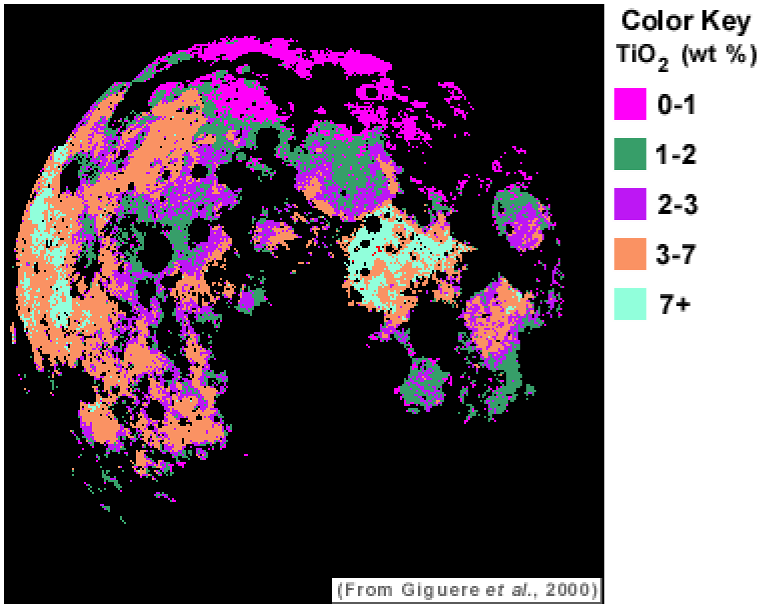

**Above:** Analyses of rock samples returned from the Moon suggest that basalts from the lunar maria are either high or low in titanium. Few samples plot in the gap between the two prominent peaks on this frequency histogram.

This two-peaked (or 'bimodal') distribution of $TiO_2$ concentrations in lunar basalts had become embedded in our thinking about the Moon. Because magmas are created by partial melting deep inside a planet, most investigators reasoned that the two groups must have formed from two compositionally distinct rock types in the lunar mantle. One was low in titanium, the other high. Some smearing out of titanium occurred by mixing of magmas from the two sources, or even by mixing of the two sources by solid convection in the mantle. It was still surprising that so few lavas had intermediate titanium contents. It turns out that lots of lavas have intermediate titanium.

## A Global Assessment of Titanium

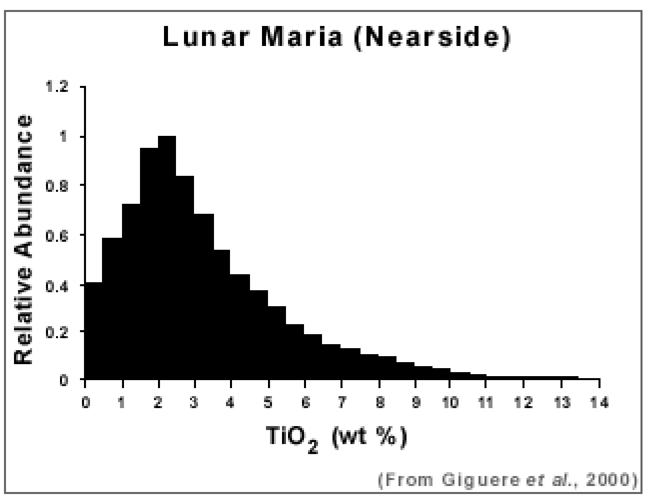
Paul Lucey (U. Hawai'i) has modified an established technique to determine the $TiO_2$ concentration of the lunar surface from the amount of light reflected at two different wavelengths. Working with Lucey and Brad Jolliff (Washington University in St. Louis) David Blewett (U. Hawai'i) used samples from known locations on the Moon to calibrate the technique [See PSRD article: Moonbeams and Elements]. In essence, the method measures the amount of dark mineral grains in the lunar surface, which is related to the amount of the mineral ilmenite ($FeTiO_3$). If a dark mineral that does not contain titanium is present, the method can give erroneous results. Fortunately, ilmenite is common in all basalts returned from the Moon.

Giguere and coworkers used this technique to determine the $TiO_2$ contents of all the lunar maria. The map below shows the distribution of titanium on the Earth-facing side of the Moon, where almost all the lunar maria occur. (Because of gravitational forces, the Moon always keeps the same hemisphere facing Earth.) On the map, the colors represent different $TiO_2$ concentrations. There are large orange areas of the maria, indicating an intermediate $TiO_2$ concentration. In fact, those areas appear to be more abundant than are areas of high-$TiO_2$.




**Above:** Map of $TiO_2$ concentrations in the lunar maria on the nearside of the Moon, determined from images obtained by the Galileo spacecraft. Highland areas (black) have been masked out.

When converted to a frequency diagram, the $TiO_2$ data are strikingly different from the distribution shown by the returned samples. Low-Ti basalts are still the most abundant, but there is a continuous decrease in abundance from a peak between 2 and 3 wt%. High-Ti basalts are the least abundant. The remote sensing data for the lunar maria tend to be shifted to slightly lower $TiO_2$ values because impacts cause mixing with nearby and underlying highland rocks, which contain only small amounts of $TiO_2$, usually less than 1 wt%. Giguere and his colleagues show that on average a mare surface contains about 20% less $TiO_2$ than do the basalt lava flows making up the maria. Thus, the surface of a maria developed on lava flows that contained 10 wt% $TiO_2$ would contain only about 8 wt% $TiO_2$. Nevertheless, the relative abundance of low-, intermediate-, and high-Ti basalts remains unchanged.




**Above:** The $TiO_2$ concentrations of the maria on the entire nearside of the Moon are distributed very differently than indicated by the returned rocks alone. The two-peaked distribution shown by rocks is probably due to restricted sampling by the six Apollo and three Luna missions--they did not land on flows with intermediate titanium concentrations.

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## A Few Complications

Do we really know the composition of the basalts making up the lunar maria? Analysis of samples and the remote sensing data give very different views of the nature of mare basalts. One possibility is that the intermediate-Ti maria were created by impact mixing of low-Ti and high-Ti basalts that overlie one another or lie adjacent to one another. Certainly this is possible in some cases, such as areas in high-Ti maria near the borders with the highlands (which have very little titanium), but Giguere and his coworkers argue that it is unlikely that such mixing is so efficient that it can account for the low abundance of high-Ti basalts. Furthermore, there are sharp boundaries between low- and high-Ti maria or regions within maria, showing that the impacts do not mix thoroughly. Giguere and his colleagues conclude that the remote sensing data give an accurate picture of the relative abundance of basalts with different titanium concentrations.

The Lunar Prospector mission also measured titanium on the lunar surface, using two totally different techniques based on neutron interactions in the lunar surface rather than the light reflected from it. Although the Prospector data have much less spatial resolution (pixels about 100 kilometers across versus about 1 kilometer for the data used by Giguere), there is general agreement. However, there are some significant differences in a few areas. Nobody has yet figured out the cause of these differences, but the total area affected is small and does not alter the basic shape of the frequency histogram. In fact, none of the problem areas have intermediate $TiO_2$ contents.

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## The Lunar Interior

One of the goals in analyzing the compositions of basalt lava flows on a planet is to determine the nature of the planet's mantle. This is possible because partial melting of the interior produces magmas. Rocks melt over a range of temperatures, not all at once. The composition of the melted portion (which becomes magma) varies with the amount of melting and with the composition of the rock melting. Thus, it is in principle possible to use the compositions of basalts on the Moon to estimate the composition of the lunar interior.

The large range in titanium contents of mare basalts suggests a wide range in the titanium contents inside the Moon. Giguere and his co-authors note that the distribution of $TiO_2$ contents of mare basalts is consistent with formation of the lunar mantle rocks from a global magma ocean, coupled with sinking of dense rocks formed in it. A well-established tenet of lunar science is that the Moon was surrounded by a globe-encircling ocean of magma soon after it formed [See **PSRD** article: Moonbeams and Elements.] As this swirling, hot mass began to crystallize, minerals with high densities (olivine and pyroxene) sank and those with densities lower than the magma (especially feldspar) rose to form the initial crust. As crystallization continued, the magma became increasingly rich in $TiO_2$ until ilmenite ($FeTiO_3$) crystallized.

The first minerals to sink would have accumulated into rocks with small concentrations of titanium. When these remelted hundreds of millions of years later, they would form low-Ti basalts. About 65% of the solidified magma ocean would have consisted of such low-Ti mantle rocks, accounting for the high abundance of low-Ti basalts. In contrast, the ilmenite-bearing rocks would make up less than 10% of the solidified magma ocean, partly explaining why high-Ti basalts are not abundant. Because the ilmenite-bearing rocks would have been quite dense, they would sink through the rocks beneath them, mixing with the portions of the mantle that was poor in titanium. This would form regions of intermediate $TiO_2$ content, giving rise to the basalts with intermediate $TiO_2$ concentrations. The mixing would also decrease the volume of the mantle rich in $TiO_2$, further lowering the abundance of high-Ti basalts.

Much more research is needed on the compositions of mare basalts--one element is not enough to tell the complete story! One particularly interesting problem is the timing and spatial distribution of eruption of basalts with different $TiO_2$ contents. This will require studying each maria in detail, including the tedious task of counting craters to estimate the ages of each compositional unit in every maria.

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## New Views of the Moon

The research by Giguere and coworkers is an example of how interdisciplinary lunar science has become. It used both knowledge of lunar samples, remote sensing, and geophysics. A great deal of interdisciplinary work is being done by lunar scientists, much of it under an initiative called *New Views of the Moon.* We can expect a vastly improved understanding of the Moon's composition, origin, and geological evolution to result from the *New Views* initiative.

## Additional Resources

Giguere, T., Taylor, G. J., Hawke, B. R., and Lucey, P. G. (2000) The titanium contents of lunar mare basalts. *Meteoritics and Planetary Science,* vol. 35, p. 193-200.

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